PROJECT DESCRIPTION

1. Project goals

PROJECT RATIONALE: Understanding and predicting the major phenomena taking place in the solar corona, such as Coronal Mass Ejections (CMEs), the heating and evolution of the solar atmosphere, and the acceleration of the solar wind, are fundamental challenges to understand and predict our own star. Meeting them requires two types of measurements: 1) spectrally resolved, *simultaneous* observations of the entire corona in multiple spectral lines emitted by chromospheric to hot coronal plasmas at high spatial resolution and cadence for long periods of time; and 2) coronal magnetic field measurements. The current fleet of space instruments such as SOHO, STEREO, Hinode, and SDO have provided a wealth of new observations to advance the understanding of the Sun. However, they all suffer from three main limitations:

A) EUV narrow-band imagers provide simultaneous 2D images of the solar corona, but they lack the necessary plasma diagnostic capabilities that only spectroscopy can provide;

B) High-resolution EUV spectrometers have the required diagnostic potential, but their very narrow field of view makes it impossible both to properly observe fast evolving phenomena like CMEs, and to obtain continuous and simultaneous coverage of the entire corona.

C) No instrument can measure the major player in coronal physics: the coronal magnetic field.

Visible coronographs, by utilizing tunable filters, can address all three limitations by providing 2D images of the whole field of view at a single wavelength, and can spectrally resolve individual lines simultaneously across the entire field of view; also, visible lines allow the measurement of the magnetic field.

PROJECT GOALS: The proposed four-year program has two overarching goals:

First goal: the Coronal Multichannel Polarimeter (CoMP), a visible light coronograph and filter polarimeter currently deployed at Mauna Loa Solar Observatory which already routinely measures the Stokes I, Q, U, V parameters between 1.05 and 1.38 solar radii, will be upgraded to include multiple chromospheric, transition region and coronal lines;

Second goal: A joint data distribution and analysis center will be built at HAO and the University of Michigan, that will distribute to the Heliophysics community: 1) data from the Upgraded CoMP (UCoMP), and 2) tools for spectroscopic diagnostics, data analysis and modeling, to be used to advance the understanding of the physical processes of the Sun.

INTELLECTUAL MERIT: UCoMP will combine the strengths of both EUV high resolution spectrometers and EUV imagers in one single instrument, and will provide the community with data analysis and modeling tools as well as unique measurements (unavailable from space instruments) of: A) magnetic field; B) plasma velocity vector; C) simultaneous 2D and 3D plasma thermal structure of the whole solar corona; D) a completely new window to study CMEs.

The technology behind UCoMP is mature, and CoMP's current deployment at one of the world's best sites for solar observations provides a unique opportunity to greatly enhance the understanding of the solar corona with a very low-risk, very high-reward instrument upgrade and data analysis center. UCoMP will also serve as a pathfinder project for the larger COSMO observatory.

The proposed facility will provide the Heliophysics community unique data, and cutting-edge analysis and modeling tools to greatly enhance the understanding of the solar upper atmosphere and of Space Weather events.

2. The advantages of tunable filter visible coronographs

Understanding the Sun and its effects on the Earth is a fundamental challenge of our time. The Sun is the ultimate driver of the physical properties and evolution of the entire Heliosphere, and can cause severe perturbations to planetary upper atmospheres due to large-scale dynamic events taking place in the solar atmosphere, such as flares and CMEs, which determine the so-called Space Weather. Our society is becoming increasingly dependent on technological assets that can be directly damaged by Space Weather events: predicting the occurrence of such events is of critical importance to minimizing their damage. Also, little is known on how the cradle of Space Weather, the solar atmosphere, is formed and maintained. For example, the mechanisms that heat the atmosphere of the Sun to multimillion degree temperatures are not known, and how the continuous outward stream of highly ionized plasma known as the solar wind is heated and accelerated is still an open question.

The limitations in the current understanding of solar coronal heating, of solar wind origin, and of CME plasma heating and acceleration are due to a fundamental lack of suitable measurements. First, a long-term set of spectrally resolved, simultaneous observations of the entire solar corona is not available, that alone can allow the development of a comprehensive picture of the physical properties of coronal plasmas as a function of time and space. Second, CME plasmas are intrinsically wildly multithermal and highly variable, but observations that allow the measurement of the rapid time evolution of their physical properties close to the Sun, where most of the physics that generates and heats CME plasmas takes place, are still unavailable.

The bulk of the emission of the solar upper atmosphere occurs in the X-ray, EUV and UV wavelength ranges. The current fleet of space instruments observing at these wavelengths has provided an enormous amount of data and has allowed significant progress; however, it is still not meeting our needs, because of the intrinsic inability of EUV instrumentation to combine within one single optical design a) the necessary high-resolution spectroscopy and plasma diagnostics capabilities, and b) simultaneous 2D imaging of the entire solar corona. Currently available coronal imagers provide simultaneous 2D images of the solar corona, but lack the necessary plasma diagnostic capabilities that only spectroscopy can provide. High-resolution spectrometers have the required diagnostic potential, but their fields of view consisting of a narrow slit make it impossible to properly observe quickly evolving phenomena like CMEs, and to obtain continuous and simultaneous coverage of the entire corona. Finally, the short wavelength of this radiation does not allow us to observe the major player in the physics of the solar corona: the coronal magnetic field.

Ground based coronographic observations of visible lines emitted by the solar corona can overcome most of these limitations. First, visible spectral lines retain the full diagnostic potential of EUV spectral lines, and through the use of visible tunable filters they can at the same time be

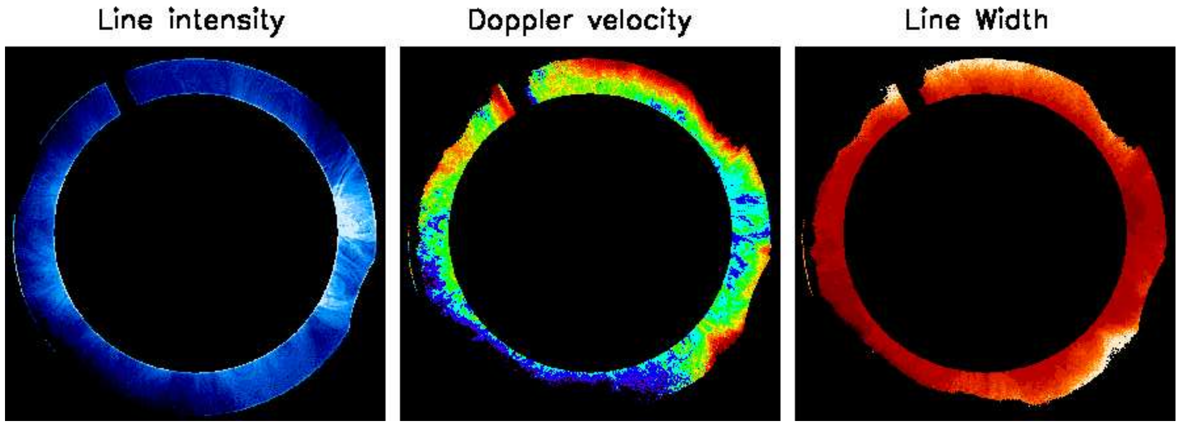

Fig. 1.— CoMP simultaneous measurements of spectral line parameters for Fe XIII 10749 Å: line intensity (left), Doppler velocity (middle) and line width (right).

resolved in wavelength and be observed simultaneously across the entire 2D field of view allowed by the coronograph. Second, visible/infrared magnetic dipole lines allow the detection of the effects of the magnetic field on visible spectral line intensity, polarization, and profiles, and thus allow for systematic observations of the coronal magnetic field. Third, at large heights visible coronal lines are primarily formed by photospheric radiation absorption and thus their intensity decreases with distance from the limb much more slowly than collision-dominated EUV lines, allowing us to extend the instrument's useful field of view to much larger heights.

Using long time series of observations, a ground based tunable filter coronograph can provide *continuous measurements of plasma dynamics, magnetism and thermodynamics of the entire corona;* the ground based location of the instrument ensures easy maintenance, repairs and upgrades, and prolongs and enhances the operational life of the instrument.

3. Technical Implementation

This project consists of two goals, namely 1) upgrading the CoMP instrument to include multiple visible emission lines, and 2) building a data analysis and distribution center that provides the community with both UCoMP data and tools and models to analyze them.

3.1. First goal – instrument upgrade and operations

CoMP combines a birefringent filter and a polarimeter to form images over a 2.8 R_{sun} field of view centered on the Sun at every selected wavelength. CoMP, currently operating from the Mauna Loa Solar Observatory, provides near-simultaneous 2D measurements of line width, intensity, Doppler velocity, and Stokes Q, U, V parameters of the entire corona from in the 1.03-1.38 R_{sun} range using the 10747 Å and 10798 Å Fe XIII coronal lines, and the 10830 Å He I chromospheric line (Tomczyk *et al.* 2008). Fig. 1 shows an example of line intensity, Doppler velocity, and width measured simultaneously by CoMP over the entire corona.

The CoMP instrument will be upgraded to extend the wavelength coverage and the number of

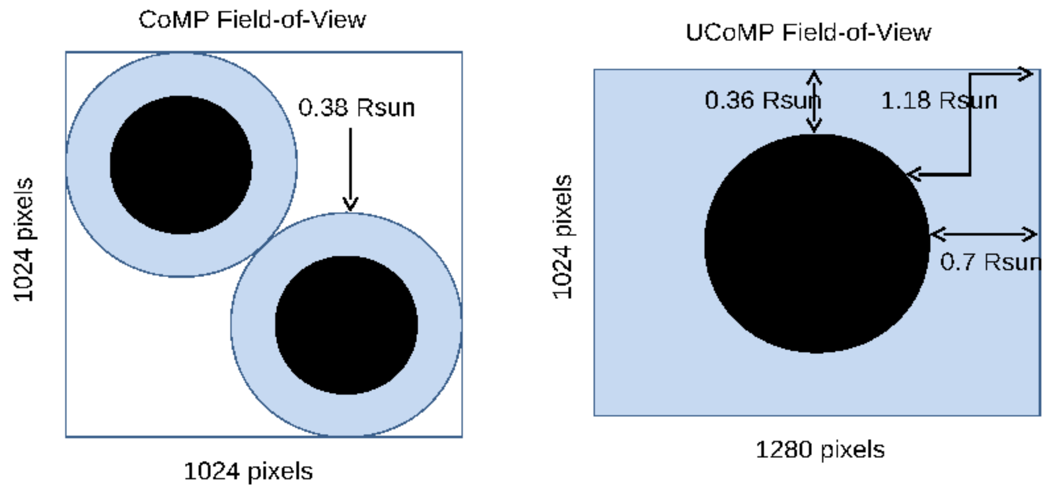

Fig. 2.— **Left:** Current field of view of CoMP: the images at the wavelength of the emission line and of the continuum are formed in the same 1024 × 1024 pixel detector. **Right:** UCoMP field of view: the two wavelengths will be imaged in two different detectors, each 1280 × 1024 pixel, resulting in a much larger field of view.

wavelengths observed by CoMP to include visible and near-IR emission lines in the 5000-11000 Å range. This upgrade will consist of replacing the detector and elements of the Lyot filter to extend the sensitivity of the instrument from the current lower limit of 9000 Å down to 5000 Å.

The lines that UCoMP will observe are emitted by the quiescent and active corona in the 0.8-4.0 MK temperature range, as well as by the core of accelerating CMEs between 0.01 MK up to ≈0.5 MK. A list of the lines that will be observed is given in Table 1, they have been observed in the past with coronographs or during eclipses. UCoMP will combine the strengths of simultaneous 2D imaging and of high resolution spectroscopy in one single instrument, and it will:

1) Provide simultaneous, spectrally resolved measurents of line intensity, width and Doppler velocity for the entire corona in multiple lines;

2) Open a completely new window in the observations of CMEs, allowing quantitative studies of their thermal structure, dynamics and evolution for the first time;

3) Deliver continuous, long-term measurements of the thermal structure of the corona over solar cycle 24 and beyond; and

4) continue the measurement of the coronal magnetic field parameters.

Only those elements of the CoMP instrument which currently limit its wavelength range will be replaced or modified. These include the detector, pre-filters, and elements of the tunable Lyot filter including the polarizers and waveplates. UCoMP will be able to observe emission lines in the 5000-11000 Å region. Emission lines will be selected with a filter wheel containing a set of 9 pre-filters. The electro-optical tuning of CoMP coupled with the filter wheel will allow observations of these lines to be made in rapid succession. Other pre-filters can be switched into the filter wheel as neeeded to allow other emission lines to be observed. A complete set of wavelength and polarization images for an emission line can be obtained with the CoMP in under one minute. This will also be the case for UCoMP.

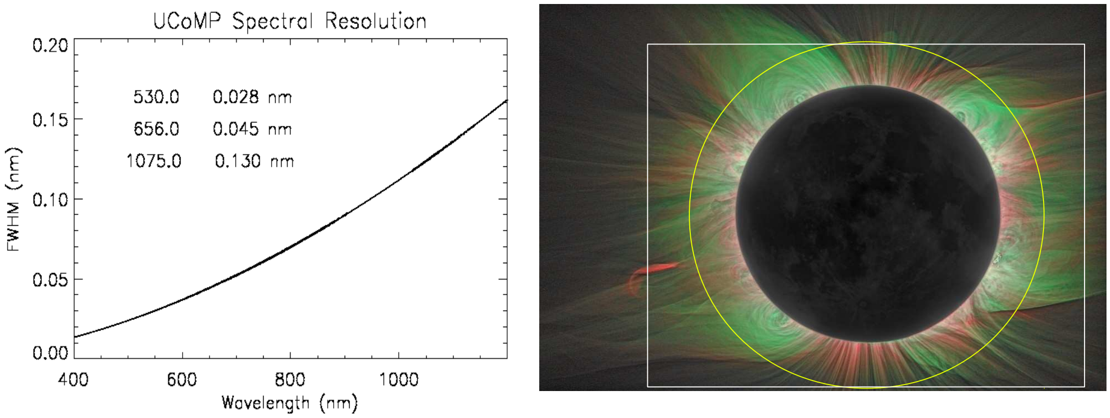

Fig. 3.— **Left:** Spectral resolution of UCoMP, as a function of wavelength. **Right:** comparison of the field of view of UCoMP (white box) and CoMP (yellow circle). CoMP field of view is similar to those of EUV coronal imagers. The image was taken by Habbal *et al.* (2011) in visible (red: Fe X 6374 Å, green: Fe XIV 5303 Å) light during the 11 July 2010 eclipse. UCoMP will allow for more comprehensive observations of streamer morphology and streamer/coronal hole boundaries, which are not possible with current CoMP and any current X-ray and EUV space instrumentation.

The extension of the wavelength range of tunable filters identical to the CoMP has already been accomplished for an instrument built by HAO for the Astronomical Institute of the Slovak Academy of Sciences, so this upgrade can be considered to be a very low risk. Recent progress in the development of poly-chromatic wavelength modulators (Tomczyk *et al.* 2010) will be utilized to modulate polarization signals efficiently over the extended wavelength range. The optics at the back end of the CoMP will need to be replaced and new hardware for holding the detectors will be fabricated. The data aquisition computer will be upgraded and will communicate with the detectors over a standard camera link interface. Most of the CoMP hardware will be reused including the coronagraph and mechanisms. The focus of the objective lens will need to be motorized to adjust for the chromatic aberration of the objective lens with the increased wavelength range of the UCoMP.

A key capability of the CoMP is to observe images of the corona in an emission line and in the continuum simultaneously. This multi-channel capability allows the removal of varying sky background and contamination by aerosols. Currently CoMP images the two channels on a single 1024×1024 pixel HgCdTe detector with a spatial sampling of 4.5 arcsec per pixel. The current field-of-view (FOV) is approximately 1.38 solar radii with a circular geometry which encompasses the corona at all azimuths. This is illustrated in Figure 2 (left). The upgraded CoMP will replace the current detector with a pair of 1280×1024 InGaArS Vis/SWIR detectors made by Goodrich. The spatial sampling will be 2.55 arcseconds per pixel and the FOV will have a rectangular geometry shown in Figure 2 (right). An example of UCoMP field of view is also given in Figure 3 (right), superimposed to a composite eclipse image of the solar corona (red: Fe X 6374 Å, green: Fe XIV 5303 Å) from Habbal *et al.* (2011). The upgrade to dual detectors will enable the upgraded CoMP to have nearly twice the FOV and twice the spatial resolution. The lowest coronal height observed by UCoMP will still be 0.05 solar radii from the limb.

The UCoMP spectral resolution is shown in Figure 3 (left). The spectral resolution will be 1.3 Å for the 10747 Å 10798 Å and 10830 Å lines as it is currently, and will improve with decreasing wavelength to be 0.45 Å at H_α and 0.28 Å at the coronal green line, Fe XIV 5303 Å.

CME core		CME hot component		Quiescent corona	
Line	$\log T_{eff}$	Line	$\log T_{eff}$	Line	$\log T_{eff}$
H I 6564	4.01-4.29	Fe XIV 5303	6.15-6.49	Fe X 6374	5.80-6.24
He I 5887	4.01-4.57	Fe XV 7062	6.20-6.63	Fe XI 7894	5.92-6.30
He I 10833	4.01-4.57	S XII 7613	6.16-6.55	Fe XIII 10800 (Ne)	6.08-6.41
Ca II 8544	4.01-4.34	Ar XIII 8339 (Ne)	6.26-6.67	Fe XIII 10749 (Ne)	6.08-6.41
O II 7321	4.16-4.92	Ar XIII 10143 (Ne)	6.26-6.67	Fe XIV 5303	6.15-6.49
O II 7332	4.16-4.92	Ca XV 5446 (Ne)	6.44-6.84	Ar X 5535	5.86-6.42
O III 5008	4.62-5.23	Ca XV 5695 (Ne)	6.44-6.84	Ar XI 6918	6.04-6.52
Fe VI 5177	4.95-5.52			Si X 14304	5.95-6.34

Table 1: Visible lines that will be observed by UCoMP. Wavelengths are in Å. Lines from the same ion indicated with "Ne" provide density sensitive line pairs. $\log T_{eff}$ indicates the temperature range where each ion has fractional abundance 0.01 or larger under equilibrium conditions.

Instrument operations: CoMP is currently deployed and fully operational at the Mauna Loa Solar Observatory. The increased data volume produced by the new coronal channels will be stored at the existing facilities at HAO that already store the CoMP data. Thus, the upgraded instrument will require no additional funding for operations and data storage.

3.2. Second goal – Data distribution and analysis center

The CoMP team currently maintains a website where the observations are freely distributed to the community. In this website, the Daily Dynamics Archive contains all processed Level 2 FITS files for each observing day; in each FITS file there are binary extensions of peak intensity, edge enhanced peak intensity, corrected line-of-sight Doppler velocity, and line width. In the Daily Polarization Achive, all processed Level 2 FITS files for each available day are distributed, including peak intensity, edge enhanced peak intensity, line integrated Stokes Q, line-integrated Stokes U, and total linear polarization $L_{tot} = \sqrt{Q^2 + U^2}$.

The available website, as well as the data format and organization will be expanded to distribute to the Heliophysics community both the data from the new spectral lines added to UCoMP (see Table 1), as well as UCoMP diagnostic products and data analysis and forward modeling tools. The diagnostic tools and products that will be distributed along with the data will be:

1. Magnetic field measurements;
2. Plasma diagnostic tools;
3. Three-dimensional tomographic reconstructions of the coronal emission;
4. The FORWARD coronal modeling and visualization package;
5. The AWSoM global coronal models; and
5. The AWSoM CME data-driven modeling.

3.2.1. Magnetic field measurements

CoMP routinely measures and delivers to the community the four Stokes parameters in the Fe XIII spectral lines. The relationship between these measurements and the 3D magnetic field is complicated, it has been discussed at length by many authors (see Judge 2007 and Judge *et al.* 2013 for reviews). The Stokes V signal, generated by the Zeeman effect, constrains the line-of-sight component of the magnetic field. It is intrinsically weak and measurements must achieve S/N ratios of order 10,000:1. Whether measurement of the line-of-sight magnetic field in the corona with a small aperture coronagraph like CoMP is possible on any given day depends on the brightness of the corona, the strength of the line-of-sight magnetic field and the number of hours available with pristine sky conditions.

UCoMP will observe more lines than Fe XIII, but given the difficulty of the measurement, it seems unlikely that the S/N required for Stokes V detection over large portions of the coronal plasma will be reached on a daily basis. This will best be left to a larger telescope aperture such as will be provided by the COSMO large coronagraph. This is beyond the scope of the present proposal. The Q and U signals, formed by anisotropic scattering of photospheric radiation, are orders of magnitude larger. A complete set of IQUV measurements for one line allows one to determine the line of sight magnetic field (from V) and the direction of the field vector to within a 90 degree ambiguity in the plane of the sky (Q and U). While not a vector field, this is a vast improvement over the guesswork involved with plasma loop morphological studies, for example.

However, because of these intrinsic limitations, considerable effort has been put into studying the role of additional data using the inverse strategy to constrain the thermal and magnetic state of the corona. Judge *et al.* (2013) have proposed a combination of lines, selected for UCoMP, whose dependencies on plasma and magnetic properties allow for the determination of the 3D vector field using tomographic techniques. Solar rotation is used to sample different lines of sight (see section 3.2.3 for plasma properties). Even in the absence of rotational coronagraphy, single epoch observations show considerable promise since one can, in principle, solve for the atomic alignment in a variety of spectral lines. Even in the absence of regular Stokes V detections, this can resolve the well known 90 degree Van Vleck ambiguity. Coupled with tomography, even noisy Stokes V measurements can reveal the vector field in the coronal volume (Judge *et al.* 2013).

Another strategy is to use forward models (Judge *et al.* 2006; Judge 2007) where additional information enters through a physical calculation of the plasma and magnetic field. Yet another dimension of the data revealed by CoMP is the detection of wave modes with periods near 5 minutes and the determination of dispersion relations allowing us to probe the magnetic field via the entirely independent method of seismology. UCoMP will detect waves across a broader variety of coronal temperatures than CoMP currently can.

With UCoMP the use of the other lines listed in Table 1 for magnetic field diagnostics will be investigated: these lines all have different sensitivities to magnetism and thermal conditions, allowing us to determine properties of the atomic alignment factor that is so important to a correct interpretation of the full Stokes vector (Judge 2007). Of special interest will be the observations of polarization in the allowed H I, He II and Ca II lines in erupting prominences during CME onset. By being emitted by a localized structure, these lines can help make the problem presented by inverting Stokes parameter measurements tractable, so that the magnetic field of the flux rope enveloping the erupting prominence can be determined.

3.2.2. Plasma diagnostic techniques

An array of existing spectroscopic diagnostic techniques can be applied to UCoMP data to determine the coronal plasma properties. Most of these techniques can be equally applied to original 2D images as well as to each voxel of a 3D reconstruction of the entire corona. These diagnostic techniques are fully described in Judge (2007) and Phillips *et al.* (2008).

3D determinations of plasma velocity: Plasma motions in the plane of the sky seen through series of images can be combined with Doppler shifts from line centroid measurements to reconstruct the velocity vector in the entire field of view simultaneously, and used to determine velocity fields in quiescent coronal structures and the acceleration of all CME components during onset.

Wave damping and unresolved motions: UCoMP's capability to measure line widths will allow studies of non-thermal velocities everywhere in the field of view, to determine the extent of wave damping in the solar atmosphere, the presence of turbulence, and the effects of CME-related shocks, while intensity fluctuations allow tracking the presence of compressional waves.

Density diagnostics in 2D and 3D: Intensity ratios from pairs of lines from the same ion can be used to determine the electron density of the plasma simultaneously in the whole corona. CoMP already provides the Fe XIII 10800/10749 ratio; UCoMP will extend this capability to other ions formed at larger temperatures, enabling the determination of the density of hot streamer plasmas and reconnection-heated CME plasmas (see Table 1). Line intensity ratios can be directly applied to 2D images and 3D reconstructions of the entire corona to determine the local electron density. Comparison with polarization brightness measurements of the electron density can provide direct measurements of the plasma filling factor.

Thermal structure of the corona: Standard diagnostic techniques can be applied to intensities from multiple ions formed at different temperatures to determine the distribution of plasma with temperature across the entire 2D coronal image. The application to 3D reconstructions of multiple line emission will result in the local determination of the plasma thermal structure everywhere in the corona, removing the problem of line-of-sight integration.

Thermal structure of CME plasmas: The availability of lines formed at temperatures ranging from 0.01 to 4 MK in Table 1 allows the determination the thermal structure of all components of a CME at all times during onset: CME front, cavity and core, as well as the current sheet behind the core itself. The presence of lines formed at multimillion degrees allows the detection of the signatures of shock-related and reconnection-related heating, the presence of a population of seed particles for SEP formation and their location relative to the CME components.

Element abundance diagnostics: The presence of elements with First Ionization Potential (FIP) ranging from 6 eV to 25 eV allows the measurement FIP-related element fractionation everywhere in the corona, to study its evolution with time, and to relate element fractionation in the solar wind source regions to values measured in the Heliosphere by in-situ instrumentation.

Magnetic field diagnostics: Magnetic field measurements are routinely carried out by CoMP combining the Zeeman effect and the scattering polarization of forbidden Fe XIII coronal emission lines (Judge 2007, Tomczyk *et al.* 2008). These measurements will continue to be carried out by UCoMP, and will be extended to the lines studied by Judge *et al.* (2013).

Solar wind diagnostics: Magnetic field measurements will be combined with 3D maps of individual line intensities, and propagated through global magnetic field models into the Heliosphere to the location where in-situ instrumentation (on board ACE and STEREO, as well as future missions) measures the composition of the solar wind. Charge state composition evolution in the accelerating solar wind can be calculated along the field line that connects the in-situ instrument with the solar corona, and used 1) to compare predicted frozen-in charge states with in-situ measurements, and 2) to calculate visible line intensities to be compared with the average 3D reconstructed emission along the magnetic field line. Comparison will provide empirical models of the temperature, density and velocity of the accelerating solar wind (Landi *et al.* 2012).

3.2.3. 3D Tomographic reconstructions of the solar corona

UCoMP line intensities will be processed using the 3D tomographic reconstruction software developed by the University of Michigan. This technique, thoroughly described in Frazin *et al.* (2009), is mathematically similar to CAT scans in medicine: it utilizes the view angles provided by the Sun's rotation over a month, and reconstructs the 3D distribution of the intensity.

This technique has been applied to narrow-band images from SOHO/EIT, STEREO/EUVI, LASCO, as well as SDO/AIA, resulting in the determination of the 3D average structure of the solar corona in white light as well as in narrow-band EUV emission. The application of 3D tomography to UCoMP data is straightforward, and can be carried out for each of the observed lines. Also, it can be extended to the available Fe XIII intensity images already taken by CoMP to date.

Available CoMP observations from 2010 to date show that data gaps due to weather limitations at Mauna Loa do not compromise 3D reconstructions and are not a significant obstacle to our goals.

3.2.4. FORWARD modeling

MHD models can quantify the distribution of coronal plasma properties such as density, temperature, and magnetic fields. Constraining models with data is complicated by line of sight integrations and non-linear, non-unique relationships between plasma, magnetic field and the emerging radiation. In addition, the projection of structures along the observer's line of sight in the optically-thin corona introduces ambiguities. These issues may be addressed via forward modeling, which allows a direct fit of a model's prediction to observations, and a means for testing whether observations can distinguish between different models.

A suite of solarsoft IDL forward modeling codes was developed to enable side-by-side comparisons of model predictions and data. This FORWARD tree includes a set of analytic MHD models (Gibson & Low 1998, Lites & Low 1997, Low & Hundhausen 1995, Gibson *et al.* 2010) and the capability to incorporate the output from numerical MHD simulations or potential-field extrapolations. These models are used to predict observables, including EUV (both broad-band

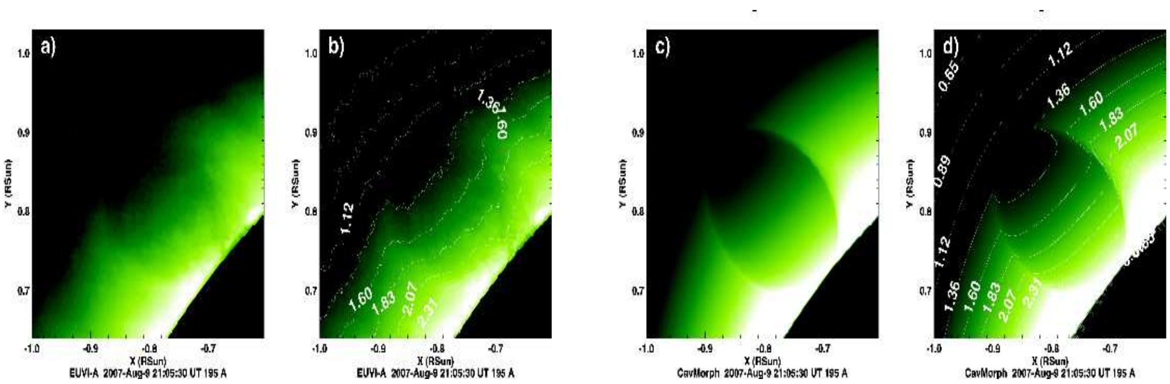

Fig. 4.— **(a)** EUVI-A image of the coronal prominence cavity analyzed in Gibson *et al.* (2010) with **(b)** intensity contours overlaid. **(c)** Forward modeled (line-of-sight integrated) EUV emission using model density and temperature with **(d)** intensity contours overlaid. Contours are in units of 1/DNs.

and spectrally-resolved lines), X-ray, white light, and Stokes polarization vectors. The observer's viewpoint is incorporated in the forward analysis, so that one may consider how a modeled structure would appear on the disk, at the limb, from any solar heliolatitude/longitudes (see e.g. Figure 4). Output is in a variety of forms, enabling easy creation of movies, Carrington maps, or simply observable information at any particular point in the plane of the sky.

The FORWARD tree has broad applicability to coronal observations in general, and has been designed for ongoing expansion. FORWARD capabilities will be extended to UCoMP lines. Using CHIANTI, FORWARD will model both thermal emission and photoexcitation, with temperature, density, and distance from the Sun explicitly incorporated into the integration along the line of sight. In this way limits on the expected flux of UCoMP lines can be established, using realistic coronal models of density and temperature (e.g., Figure 4).

3.2.5. Global coronal modeling

The unique observations provided by UCoMP can be used to drive global models of the solar corona, by combining them with calculations from the Alfvén Wave Solar Model (AWSoM, Sokolov *et al.* 2013, van der Holst 2010), an advanced 3D MHD numerical model that includes the chromosphere, transition region and low corona in a self-consistent, multi-species, multi-temperature approach. This model treats ions and electrons as two separate species with the same bulk velocity, collisionally coupled thermodynamics, and heat conduction applied only to electrons (van der Holst *et al.* 2010). A WKB treatment of Alfvén waves is included in the model where dissipation of the waves heats the corona and accelerates the solar wind by the Alfvén wave pressure gradient. A separate equation is solved for Alfvén wave transport and self-consistently coupled to the MHD equations through source terms. Two types of dissipation processes are taken into account: (i) Kolmogorov-type dissipation (Hollweg 1986) that is independent of the propagation direction of Alfvén waves, and (ii) counterpropagating wave dissipation that is only effective when Alfvén waves propagate in both directions along a magnetic field line (cf. Isenberg 1987). Boundary conditions are specified in the upper chromosphere: uniform, outward propagating Alfvén wave energy density at the solar surface as inferred from observations (McIntosh *et al.* 2011), and synoptic magnetograms to specify the radial magnetic field at the inner boundary. Comparison between AWSoM predictions and UCoMP data can be used to constrain the AWSoM model input parameters and improve the final model calculations, to be used to determine the properties of the inner Heliosphere and to directly and quantitatively link coronal observations with in-situ instruments.

3.2.6. CME modeling

UCoMP opens two entirely new windows to study and model CMEs. First, by combining plane-of-the-sky motions and Doppler shifts, it provides the first ever continuous measurements of 3D velocity of the CME during onset. Second, by fully resolving spectral lines sampling the 0.01-6 MK range simultaneously everywhere in the CME, it allows the complete determination of the thermal energy budget of all CME components during onset: erupting prominence, reconnected plasma, current sheet, and it can even detect shocks and their locations from spectral line widths.

These unique observations will be used to advance our understanding of CME initiation and evolution by combining them with CME simulations from AWSoM. CME simulations done within the AWSoM framework have initially been performed with flux ropes prescribed in an initial state of force imbalance (e.g. Manchester *et al.* 2004a,b, 2008, 2012). While these simulations have provided understanding of CME propagation, they do not address the process of initiation. For the simulations proposed here, shear and rotational flows will be used to simulate CME events so that the early phase of CME liftoff can be accurately captured. This follows from our earlier studies (van der Holst *et al.* 2009) of breakout CME initiation (Antiochos *et al.* 1999). Many studies have demonstrated that breakout reconnection produces fast ejections in both 2.5D and 3D geometries, in a variety of multipolar topologies, with and without the solar wind (Antiochos *et al.* 1999; MacNeice *et al.* 2004; DeVore & Antiochos 2005, 2008; Lynch *et al.* 2008, 2009; van der Holst *et al.* 2007, 2009; Roussev *et al.* 2007; Soenen *et al.* 2009). Furthermore, numerous well-observed solar eruptions agree qualitatively with the topology and expected dynamical evolution of the breakout model (Aulanier *et al.* 2000; Sterling & Moore 2001a,b,2004a,b Manoharan & Kundu 2003; Gary & Moore 2004; Deng *et al.* 2005; Alexander 2006; Mandrini *et al.* 2006; Su *et al.* 2006; Joshi *et al.* 2007).

Observation-driven CME simulations will be carried out, evolving the system in time with horizontal flow fields provided by local correlation tracking (a standard SDO/HMI data product). The form of reconnection associated with the CME, whether breakout or tether-cutting, will occur as a natural consequence of the surrounding coronal magnetic field.

A salient feature of the AWSoM model is that ion and electron temperatures are allowed to depart over the short times scales characteristic of reconnection and shock/wave propagation. This approach marks a significant advancement over previous models by correctly basing heat conduction, charge state calculations and synthetic image predictions on the electron temperature, which may be an order of magnitude cooler than the proton temperature (Manchester *et al.* 2012), as shown in Figure 5.

AWSoM CME simulations provide a level of realism that allows many direct comparisons with UCoMP observations as shown in Figure 5. Existing visualization and diagnostic capabilities allow

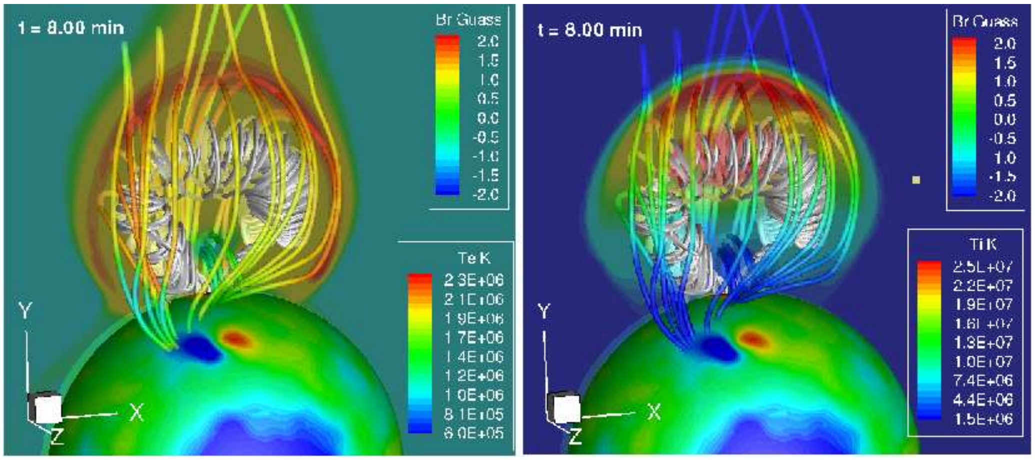

Fig. 5.— Three-dimensional views of the temperature structure of a CME simulated with the two-temperature model. The left (right) panel shows the electron (proton) temperature on the equatorial plane viewed from the north pole. The magnetic field lines of the driving flux rope are shown with white lines while the closed loops are colored to show temperature. Protons are directly heated by the shock to more than 25 MK, while electons are only briefly collisionally coupled to protons to reach a temperature of 2.3 MK.

us to generate synthetic 2D synthetic images of UCoMP lines both from the erupting CME and the background solar corona. Predicted Doppler shifts, line widths and thermal structure of all CME components will be directly compared with UCoMP measurements as a guide to improve the energy release and distribution processes in the CME model.

Common to all CME models, is that a vertical current sheet forms low in the corona after the eruption onset. The reconnection at this sheet releases most of the stored energy, because it relaxes the magnetic field back to its minimum-energy potential state. However, plasma energetics and dynamics have not been simulated fully because essential thermodynamic terms have not been included in computations to date. Our two-temperature CME model will give us the ability to close this crucial gap between theory and observations and determine where magnetic reconnection during CME onset occurs, how much it heats the plasma, and compare predictions to UCoMP observations.

4. Relationship to COSMO

COSMO consists of a suite of ground-based telescopes aimed at studying the solar corona. This suite of instruments is centered on the Large Coronograph (LC), currently in advanced planning phase, which will consist of a 1.5 m refractive coronagraph that will observe the corona from 1.03 R_{sun} to 1.9 R_{sun} with a $2''$ spatial resolution and will provide magnetic field measurements with a 10 minute cadence down to a 1 G sensitivity. The instrument will also be allowed to have an offset observation mode that will extend its field of view up to 3.8 R_{sun} to follow the evolution of CMEs at large distances.

The UCoMP project will serve as a pathfinder for the larger LC instrument. Once the one-time upgrade on the existing CoMP will be implemented, UCoMP will enable the determination of the intensity levels for the lines in Table 1 for COSMO LC instrument design; further, it will provide a testbed to experiment on other lines not included in Table 1 which could provide valuable diagnostics for the solar corona, the solar wind and CME plasmas. With its vastly larger aperture, COSMO will dramatically improve the diagnostic capabilities over UCoMP at all heights, especially for magnetic field measurements. Also, the joint HAO/University of Michigan data analysis and modeling facility will provide the necessary infrastructure to fully distribute and utilize COSMO data for space weather modeling and forecasting, and for student involvement in cutting edge scientific research.

5. Project management

5.1. Milestones

Instrument development: The upgrade of CoMP will be carried out by the HAO engineering team under the leadership of Dr. Tomczyk in the first two years of the investigation, after which the instrument will be fully operational.

Data analysis and modeling center:
First year: Tomographic techniques will be adapted to ingest COMP and future UCOMP data. Current and past COMP data will be analyzed to determine Stokes parameters. Results will be published in the refereed literature. The development of the Michigan website for data and model dissemination will begin.
Second Year: The FORWARD code will be adapted to UCoMP data; the magnetic field diagnostic properties of UCoMP lines will be investigated. Diagnostic tools and analysis software for UCoMP line intensities will be developed. The HAO and Michigan websites will be adapted to distribute UCoMP data.
Third Year: UCOMP will start observations; its data will be distributed through the Michigan and HAO websites. UCoMP and existing CoMP observations of CMEs will be compared to AWSoM modelpredictions. The Michigan website will be developed to include plasma diagnostic capabilities. Results will be published in the refereed literature.
Fourth Year: The AWSoM model will be interfaced with the Michigan website. The Michigan and HAO websites will be finalized so that UCoMP data, diagnostic tools and products, and model results will be disseminated through the Michigan and HAO websites.

5.2. Personnel

PI Dr. Enrico Landi will coordinate the University of Michigan and HAO groups, lead the development of the Michigan website for the dissemination of UCoMP data and modeling products, and the distribution of the UCoMP data from the existing CoMP website. He will directly participate in data analysis and plasma diagnostics.
Collaborator Dr. S. Tomczyk will serve as Institutional PI for HAO, and will be responsible for the instrumental upgrade of CoMP, leading the HAO engineering team.
Collaborator Dr. S.E. Gibson will be responsible for the forward modeling applications of the

FORWARD code to UCoMP data, and will disseminate the results through the Michigan and HAO websites.

Collaborator Dr. P. Judge will be responsible for investigating the magnetic field diagnostic properties of UCoMP lines. He will also integrate magnetic field diagnostics in the HAO and Michigan websites.

Co-I Dr. R.A. Frazin: will be responsible for producing and distributing 3D tomographic reconstructions of the solar corona for existing CoMP observations and future UCoMP data.

Co-I Dr. W. Manchester will be responsible for CME and global model development and comparison with UCoMP data. His AWSoM-based simulations will also be made available through the Michigan website.

6. Broader Impact

The impact of UCoMP opbservations will be similar to that of space borne EUV instrumentation, and yet it will be unique by providing the community with images of the Sun for a larger field of view while retaining the full spectral resolution. By combining these unique observations with diagnostic tools and modeling products, and distributing them in dedicated websites, this project will provide the community with an infrastructure that will enhance reaserch in many fields of solar physics and Space Weather.

The analysis of CoMP and UCoMP data, as well as the CME and global corona model development that will be stimulated by UCoMP, are ideal topics for graduate student education and dissertations. While not directly funded by this proposal, graduate students at the University of Michigan will use UCoMP data and diagnostic tools, and UCoMP-related modeling tools for their dissertations.

Undergraduate student participation will be included in this project, and it will be managed through the University of Michigan's Undergraduate Research Opportunities Program (UROP),at no cost to the present investigation. In fact, UROP pays students out of university funds and requires a report at the end of each semester, so no additional funding is required from the student's supervisor. Undergraduate student tasks are difficult to define *a-priori*, as their experience and skill levels are highly variable. Projects may include carrying out data reduction and spectral analysis on CoMP and UCoMP data; plasma diagnostics; coronal feature identification; and comparison between predicted and observed line intensities and frozen-in charge states, software testing.

7. Results from Prior NSF Support

PI Enrico Landi and Co-PI Frazin: NSF Award: AGS 1154443; Total Funding \$308,240; Funding Period: 3/1/2012 - 2/28/2015. Title: *Differential Emission Measure Determination in 3D using AIA data.* This grant is aimed at characterizing several instrumental issues of the SDO/AIA imager and to improve the temperature response functions (TRFs) of 94 Å and 131 Å channels so that the 3D DEM of the solar corona can be correctly estimated. **Intellectual merit:** To improve the AIA TRFs, a new version of CHIANTI was developed and released (version 7.1). The new version of the CHIANTI database vastly improves spectral calculations that are relevant for AIA observations, providing a large expansion of the CHIANTI models for key Fe ions from Fe VIII to Fe XIV to improve the predicted emission in the 50-170 A range. **Broader impact:** The new TRFs enable the scientific use of the two short-wavelength AIA channels for the first time, so anyone in the scientific community can now use them for diagnostic purposes. Also, CHIANTI is a spectral code freely distributed over the internet, used by the entire solar physics community. **Publications:** CHIANTI 7.1 is described in Landi et al. 2013, ApJ, 763, 86.

Co-PI Frazin: NSF grant AGS1027192; Total funding: $1,700,000; Funding period: 9/1/2010 - 9/30/2013; Title: *CDI-Type II: New Cyber Technologies to Enable Space Weather Forecasting*. **Intellectual Merit:** Most of the proposal is concerned with data assimilation for the thermosphere and ionisphere, but Frazin's portion of the project was the determination of the structure of CMEs with advanced tomography methods based simultaneous views from the SoHO and STEREO messions. A key part of this effor was inter-calibration of the STEREO/COR1 and COR2 and the SoHO/LASCO coronographs. **Broader Impact:** The project supported several graduate students. **Publications:** The project supported more than 20 peer-reviewed publications.

Co-PI Manchester: NSF Award: ATM 0642309; Total funding: $470,000; Funding period: 09/15/2006 - 09/14/2011. Title: *Comprehensive Corona and Heliosphere Model (CCHM)* **Intellectual merit:** A first-principles based comprehensive numerical model of the 3D time-dependent structure and dynamics of the slowly varying corona and the ambient solar wind based on the SWMF was developed and maintained. The code has been delivered to CCMC where is is running and available for community use. **Broader Impacts:** The project supported several Ph.D. students; the code is available to the community at CCMC. **Publications:** The project supported a total of 19 peer reviewed publications.
NSF grant number AGS 1023735; Funding: $360,000 Period: 10/01/2010 - 08/31/2013 Title: *Modeling CME Initiation with Magnetic Flux Emergence* **Intellectual merit:** The magnetic flux emergence from a turbulent convection zone to the corona was simulated in a single computational domain. It was also determined how energy is transported along magnetic field lines from the convection zone into the corona that causes a buildup necessary for eruptions such as CMEs. **Broader Impact:** The project supported Ph.D. student Fang Fang, culminating in the successful completion and defense of her PhD dissertation on April of 2012. **Publications:** The project supported 3 peer reviewed publications.

Landi, Frazin, Manchester: NSF Award: AGS 1322543; Funding: $2,500,000; Period: 2013/05/01-2018/4/30; Title: *A Modular Capability for Community Modeling of Flares/CMEs and their Interplanetary Impacts* **Intellectual merit and broader impact:** the project just started.